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Cassini's Grand Finale –

Attitude Control Subsystem Performance During Proximal Ring Plane Crossings

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The Cassini Spacecraft

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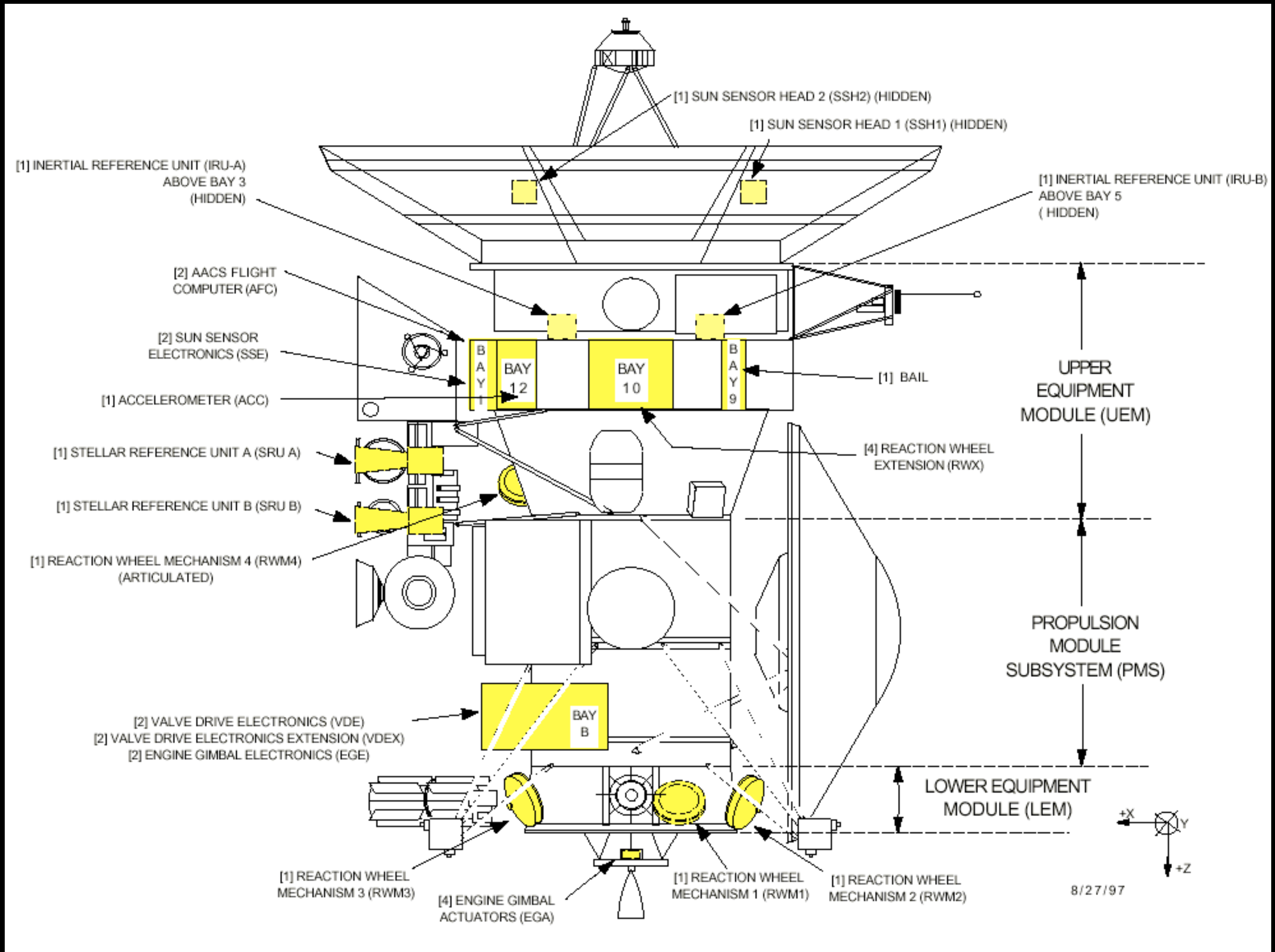
- Attitude Initialization:
  - Sun sensors
- Attitude Estimation:
  - Star trackers
  - Inertial Reference Units
- Attitude Control:
  - Reaction Wheel Assemblies
  - Reaction Control System (Thrusters)



Cassini's Grand Finale

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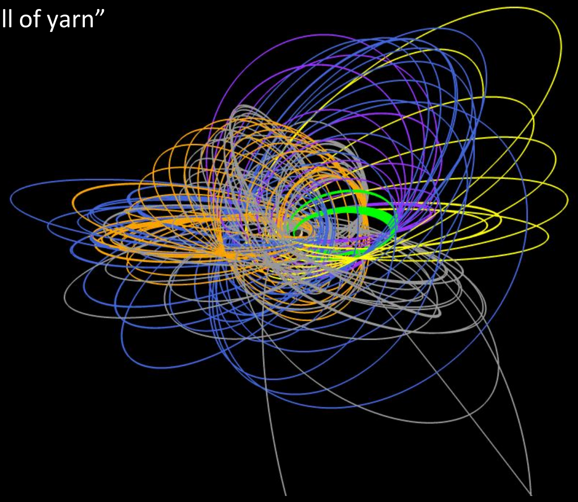
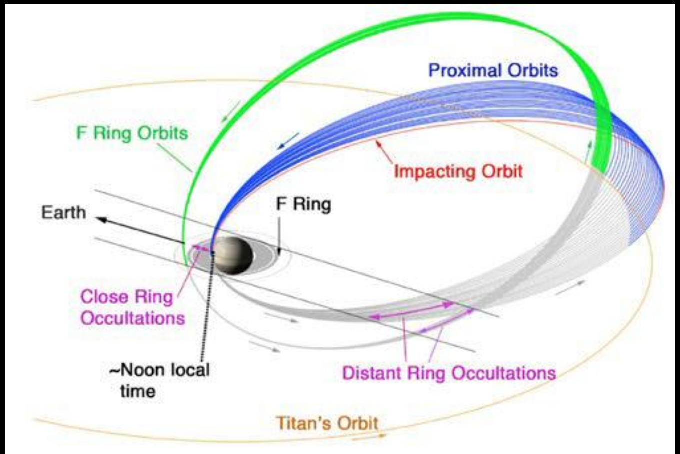
- Began April, 2017 after a final Titan close flyby of 980 km altitude, which allowed Cassini to "jump across" the rings.
- Consisted of 22 dives through the space between Saturn and its innermost D-ring.
- Ended September 15, 2017 with the final plunge into Saturn's atmosphere, concluding a remarkable 20-year-long mission.

Cassini's Orbits: 2004-2017
"ball of yarn"





Ring Grazing Orbits to the Grand Finale

Why plunge into Saturn?

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- Cassini was almost out of fuel after 20 years.
- To preserve and protect potentially habitable moons of Saturn.
- Other “end of mission” scenarios were considered:
  - Visit Jupiter, or visit Uranus and Neptune
  - Investigate Centaurs
  - Remain in a stable long-term “parking” orbit at Saturn
- But Saturn impact option offered opportunity for unique science!
  - Create detailed maps of Saturn’s gravity and magnetic fields
  - Sample icy ring particles
  - Ultra close observation of Saturn’s atmosphere
  - Sniff the atmosphere, providing science right to the end

April 22nd, 2017 - The Close Final Titan Flyby

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Source: https://saturn.jpl.nasa.gov

22 Proximal Orbits

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Source: https://saturn.jpl.nasa.gov

Risks in Proximal Orbits

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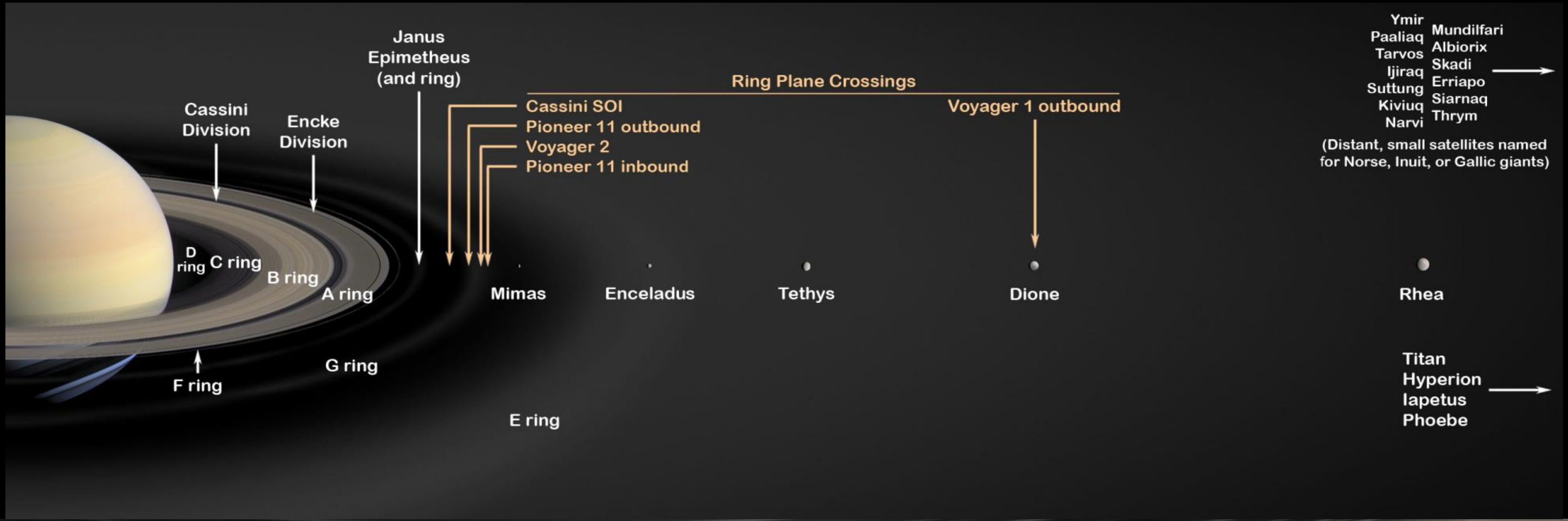
- Dust hazards in the 3000 km "clear area"
- Spacecraft controllability against Saturn atmospheric torque
- Other considerations: radiation effects, bright body interference, trajectory deviations, and fault protection response



Proximal Orbit Flyby Designs

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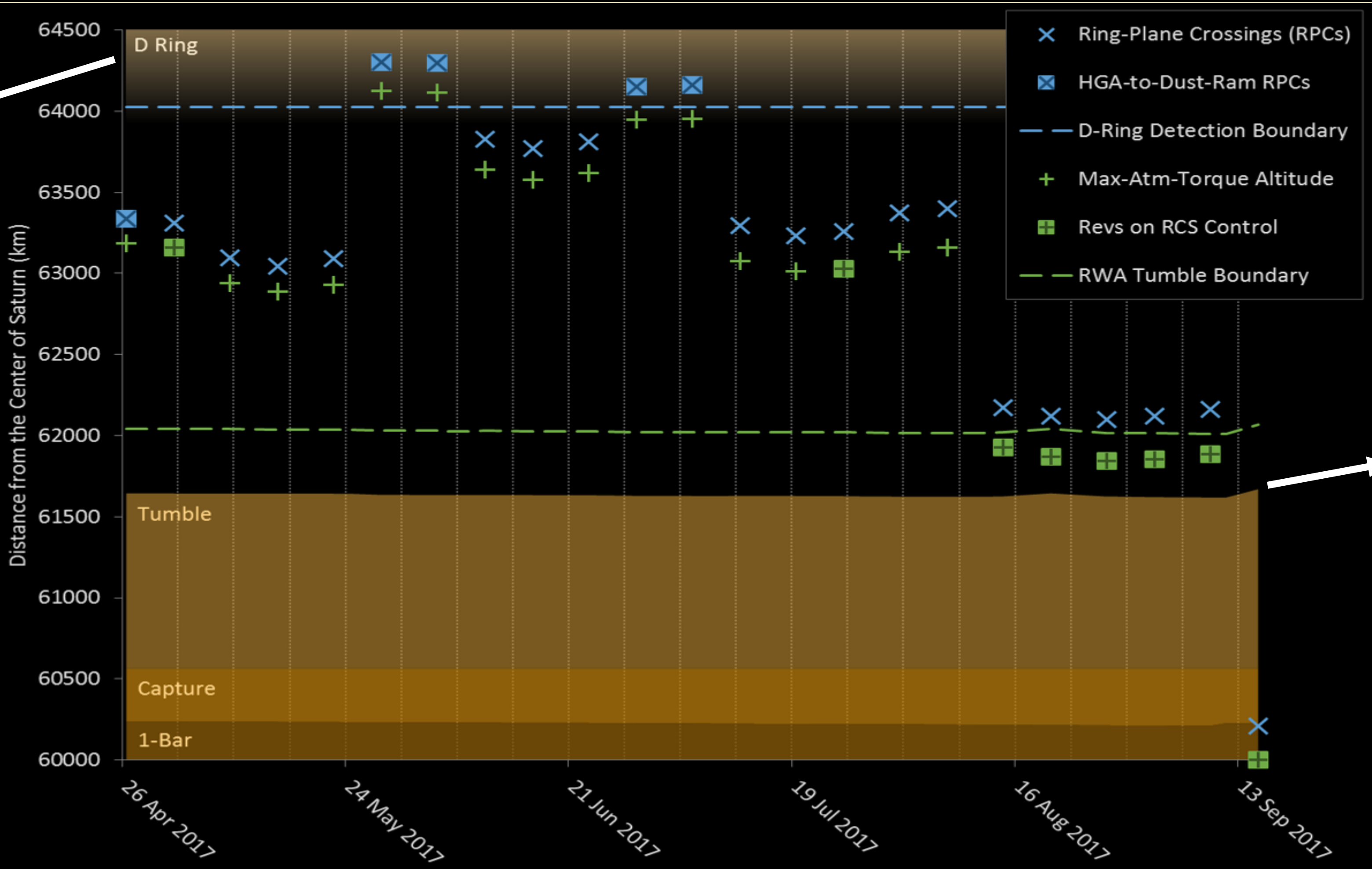
D-ring particles may cause dust impact to the spacecraft



Saturn atmospheric torque would tumble the spacecraft

Dust Hazard Mitigation

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- Cassini had many experiences with "Critical Ring Plane Crossings".
- During these dust hazard passages, Cassini took the following precautions:
  - Closed the accordion-like clamshell main engine cover.
  - Pointed the 4-meter High Gain Antenna (HGA) dish towards the dust velocity (RAM) direction as a shield to protect sensitive instruments.
  - Sun sensors were mounted in the antenna dish, so they were vulnerable to dust hazards.
- Dust environment between Saturn and the D-ring was predicted to be benign!

Critical Ring Plane Crossings

	Ring Regions*	Date
Saturn Orbit Insertion Crossings	G	7/1/04
	JE	7/1/04
	JE	7/1/04
	G	7/1/04
	E	3/9/05
	G	4/14/05
	E	9/23/05
	G	6/11/07
	G	6/28/07
	JE	6/28/07
	G	1/27/10
	G	2/13/10
	G	6/19/10
	JE	11/24/15
	JE	12/6/15
	JE	12/11/16
	JE	1/2/17
First crossing inside D -ring →	D	4/26/17
4 crossings nearest D-ring	D	5/28/17
	D	6/4/17
	D	6/29/17
	D	7/6/17

Sun Sensor Checkout

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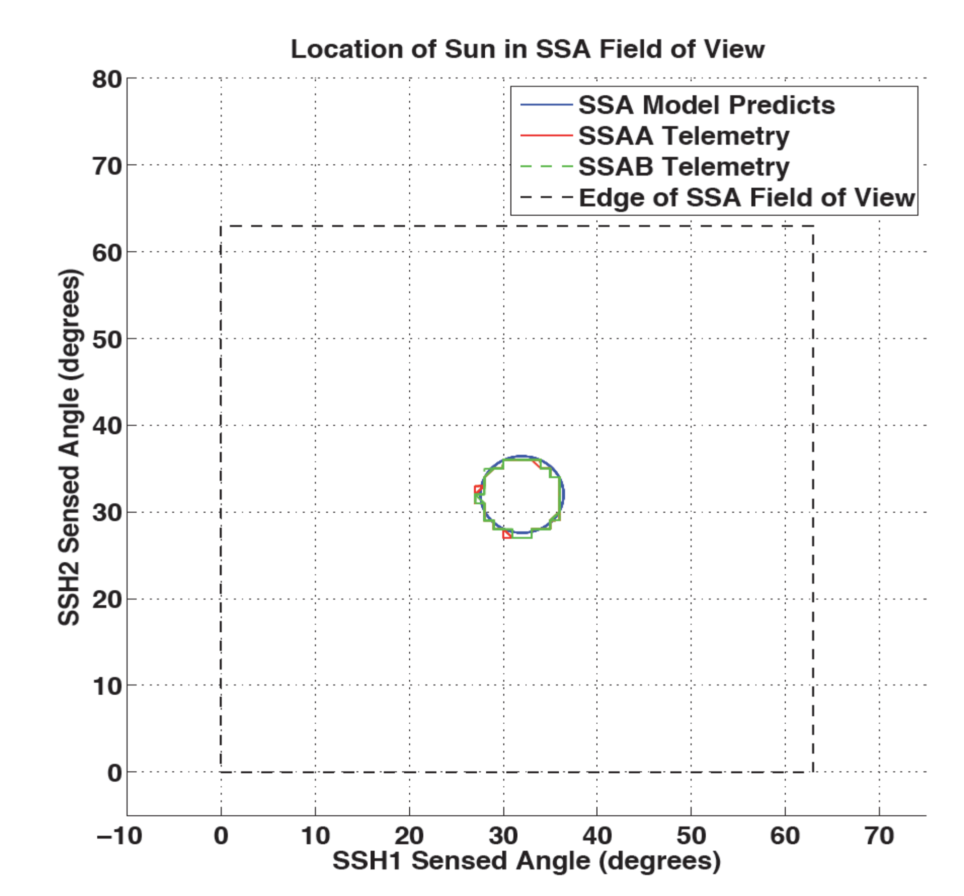
- To increase visibility of sun sensor health near the dust hazard:
  - Both prime sun sensor assembly and the backup assembly were powered on.
  - Sun sensor fault protection were disabled.
  - Sun sensor checkout activities were conducted after each critical ring plane crossings.



Sun sensor checkout post first proximal orbit ring plane crossing

“The Big Empty” Causing a Pointing Redesign

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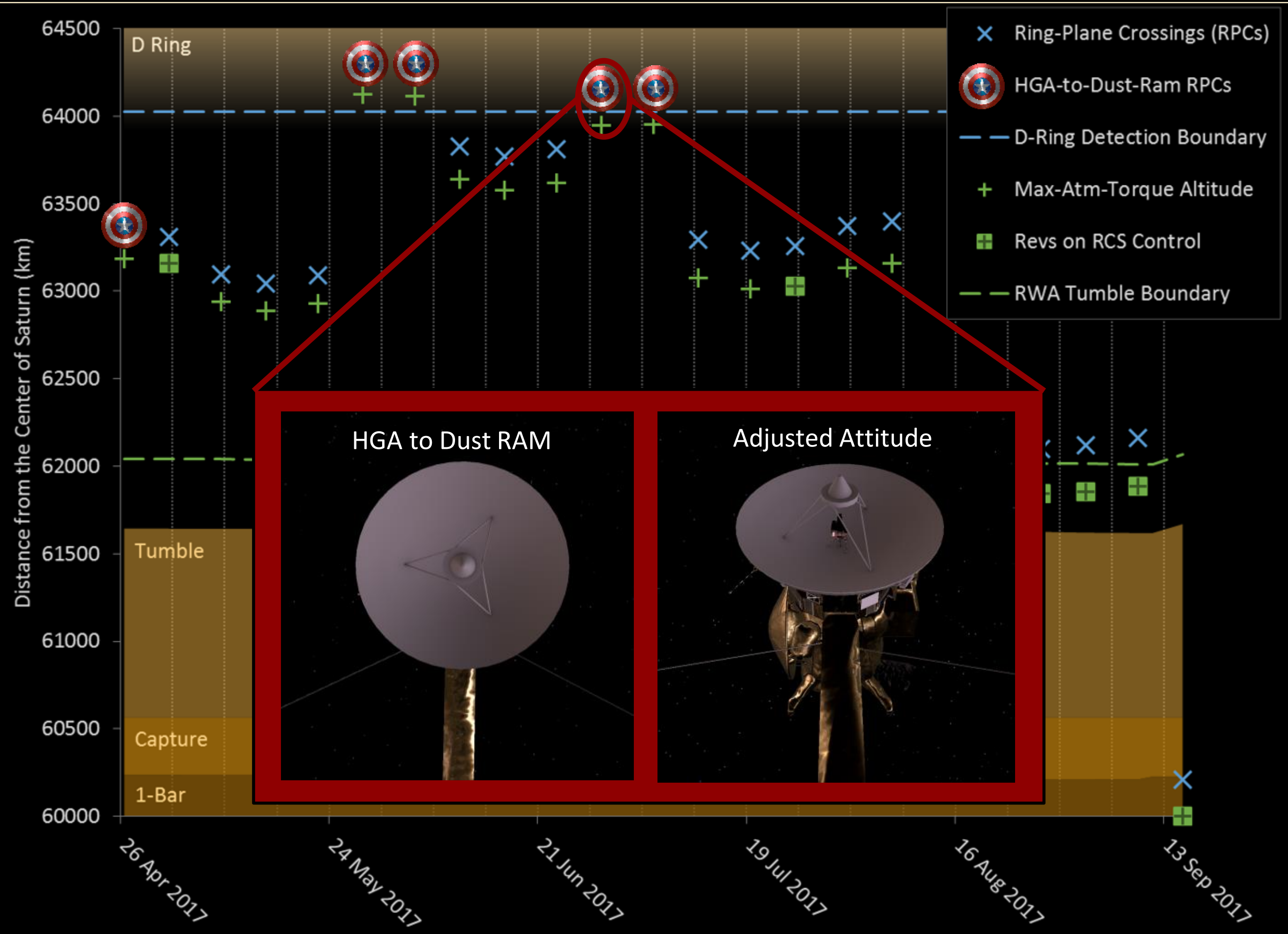

Spacecraft Controllability

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RWA

RWA	Control Authority [Nm]
RWA-1	0.165
RWA-2	0.165
RWA-4	0.165

RCS – 0.57N per thruster + 7% d[illegible]

Axes	Co[illegible]	
	Plus	Minus
X-axis	1.625	1.490
Y-axis	1.058	1.329
Z-axis	1.193	1.193

NO CONCERNS

Estimated External Torque (2008 Analysis)

Torque Sources [Nm]	Orbits 1-18 (higher altitude, quiescent)	Orbits 19-22 (low altitude)
Upper Atmosphere	0.14	0.9
Gravity Gradient	7.0e-4	7.0e-4
[illegible]	1.0e-4	1.0e-4
[illegible]	2.0e-6	2.0e-6
[illegible]arget Motion Compensation	1.3e-3	1.3e-3
Total	**0.142/0.082**(per wheel)	**< 0.99**
RWA Control	0.004	N/A
RWA Drag	0.02	N/A
Gyroscopic	0.012	N/A
Total Per Wheel	**0.118**	N/A

Final Five Orbits

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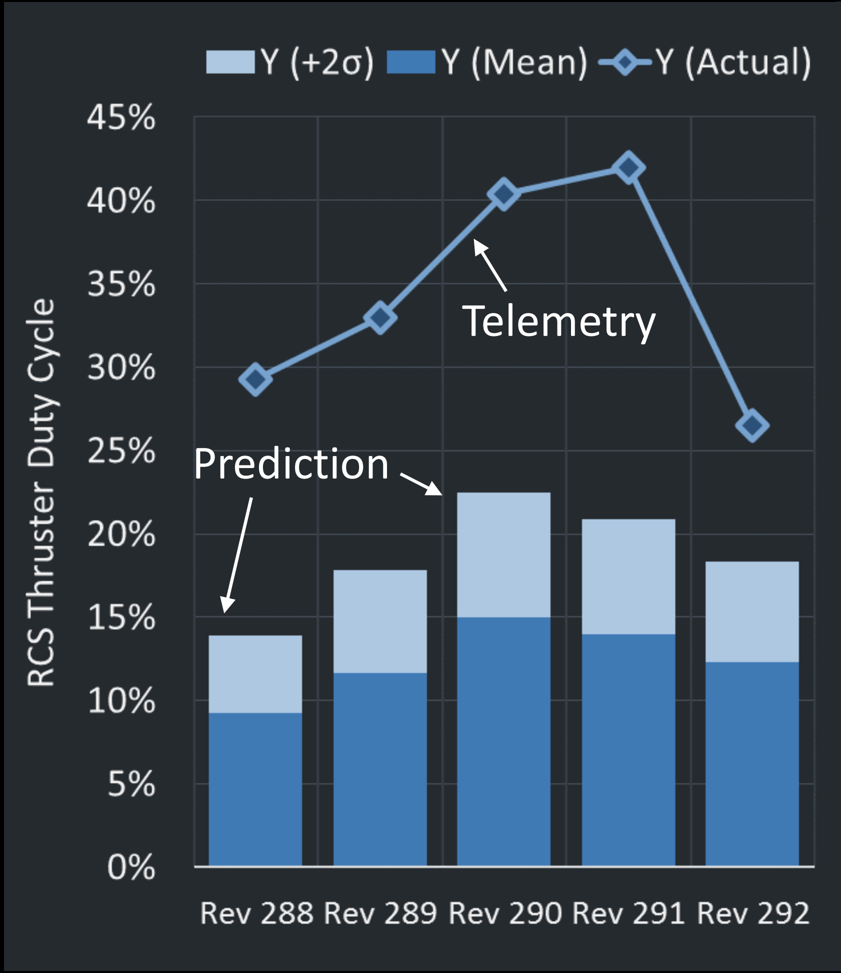
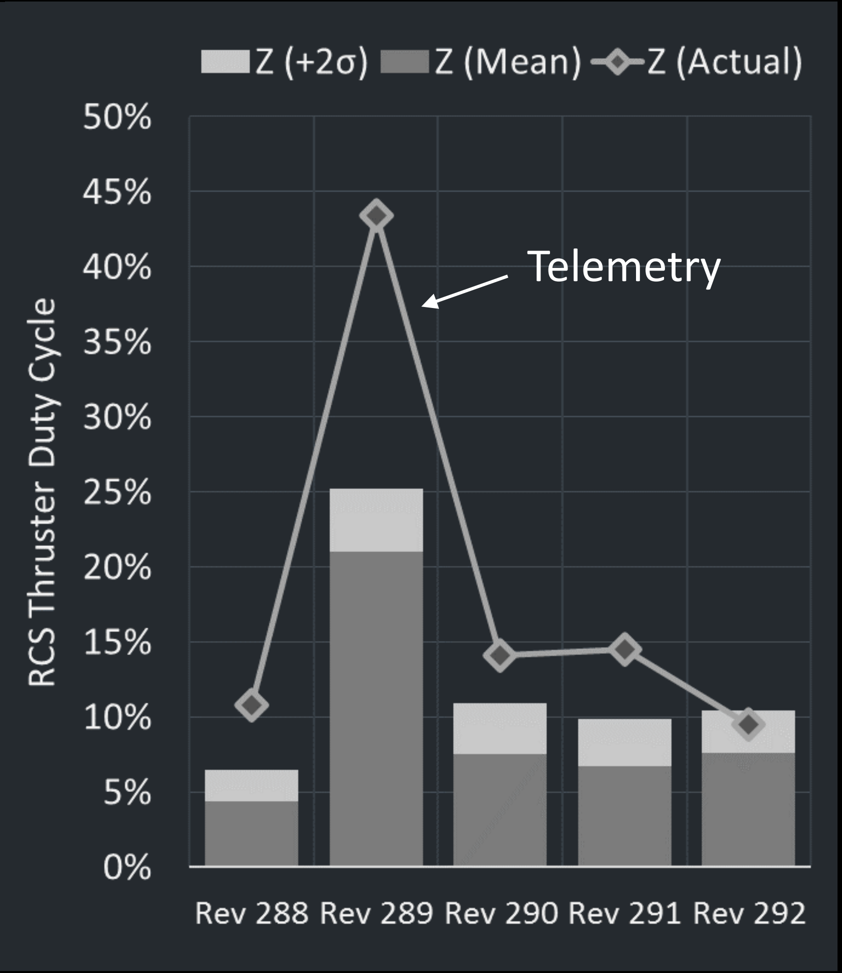
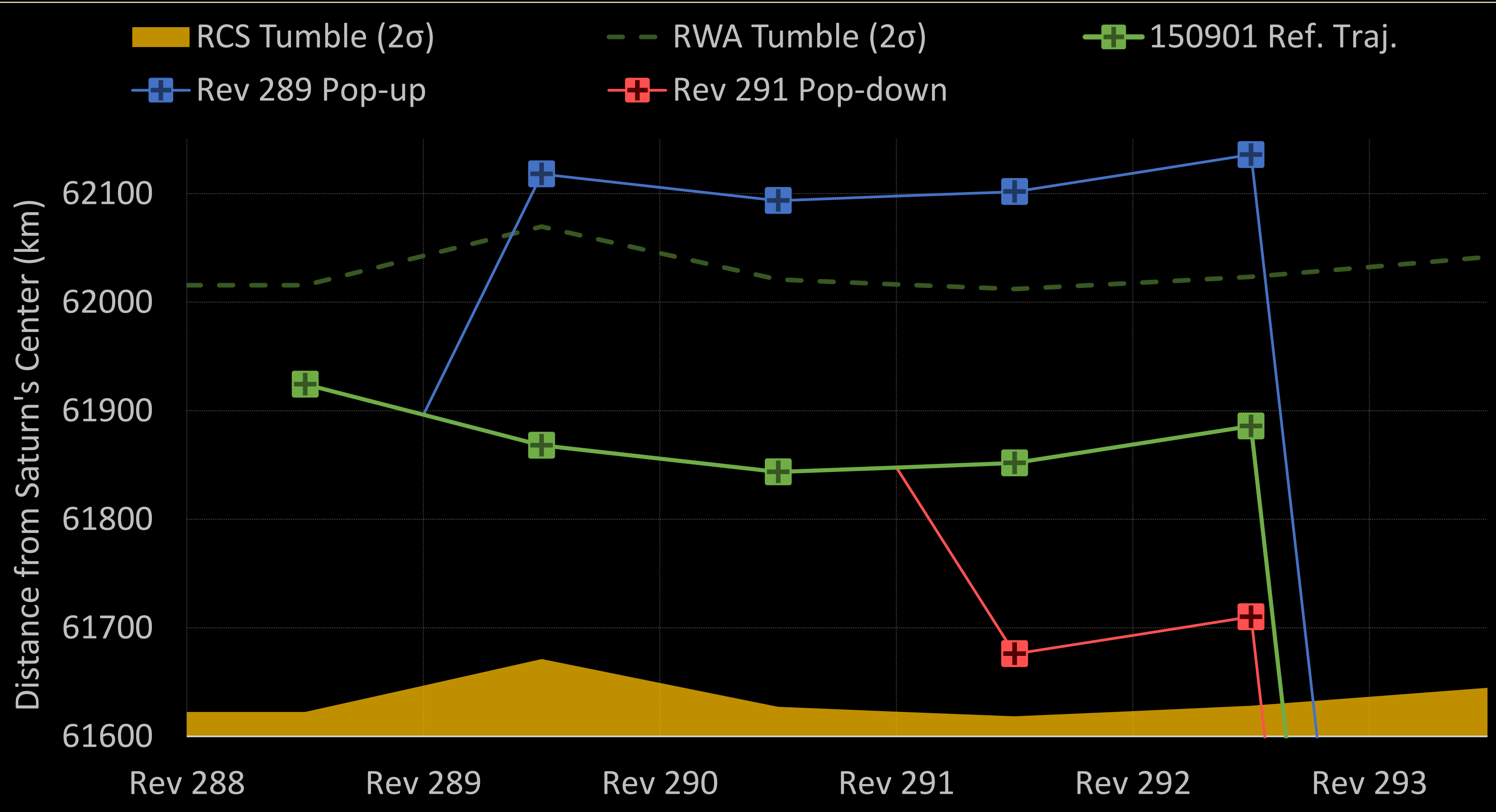




Date	Altitude (km)
Aug 14	1706
Aug 20	1652
Aug 27	1626
Sept 2	1639
Sept 9	1675
Sept 15	Plunge

Contingency "Pop Up" or "Pop Down" Maneuvers



Source: Erick Sturm
Jet Propulsion Laboratory

Sept 15th, 2017 – The Final Plunge

- 1:30 AM PDT: Final turn to –X to S/C RAM
- 4:53:45 AM: Atmosphere trips controller to "high-rate" thruster control
- 4:55:19 AM -- Final telemetry from Cassini (tumbling begins)
- 4:55:39 AM -- X-Band carrier is lost
- 4:55:43 AM -- S-Band carrier is lost


Last Telemetry – Attitude Control Error

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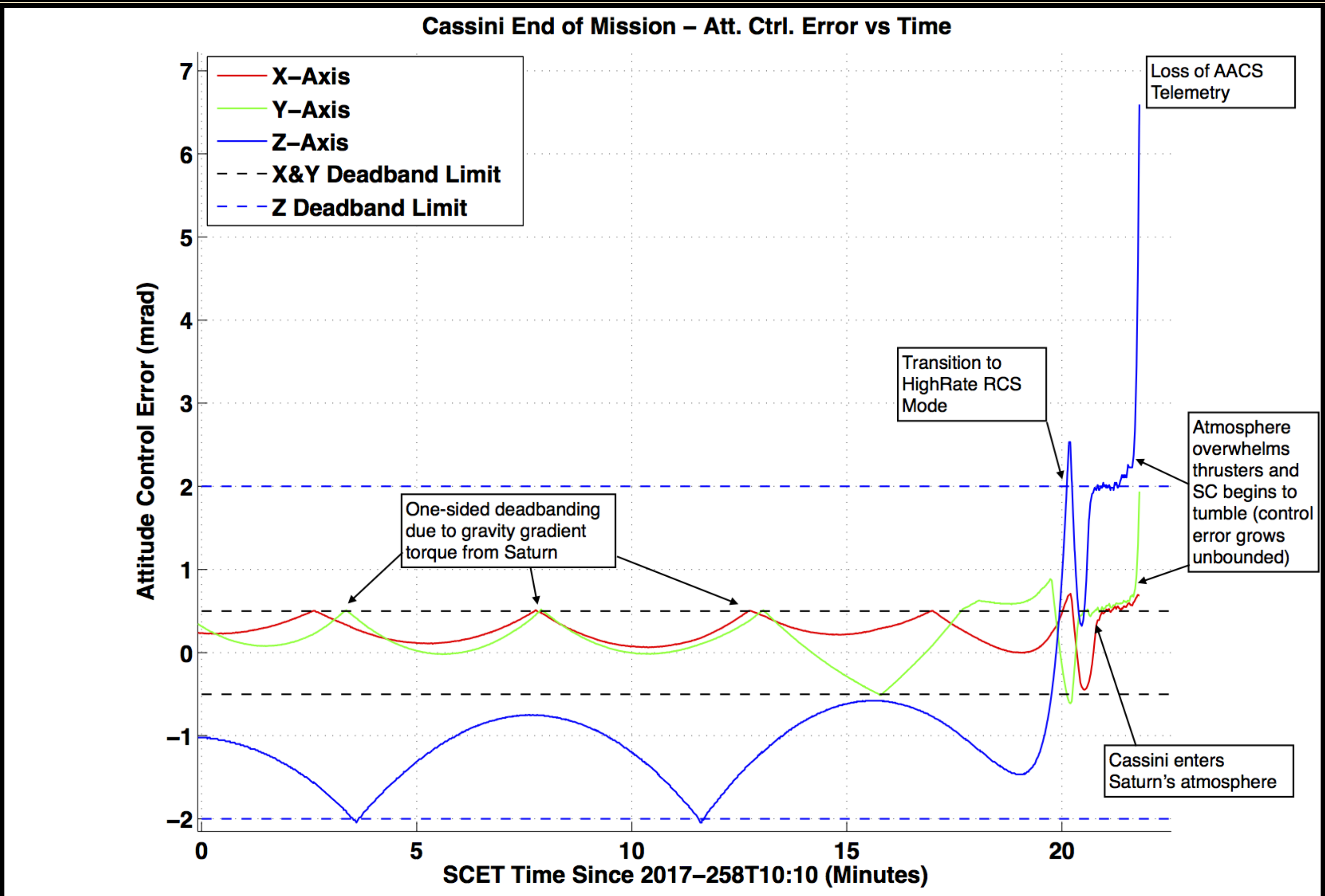

Last Telemetry – Thruster Activity

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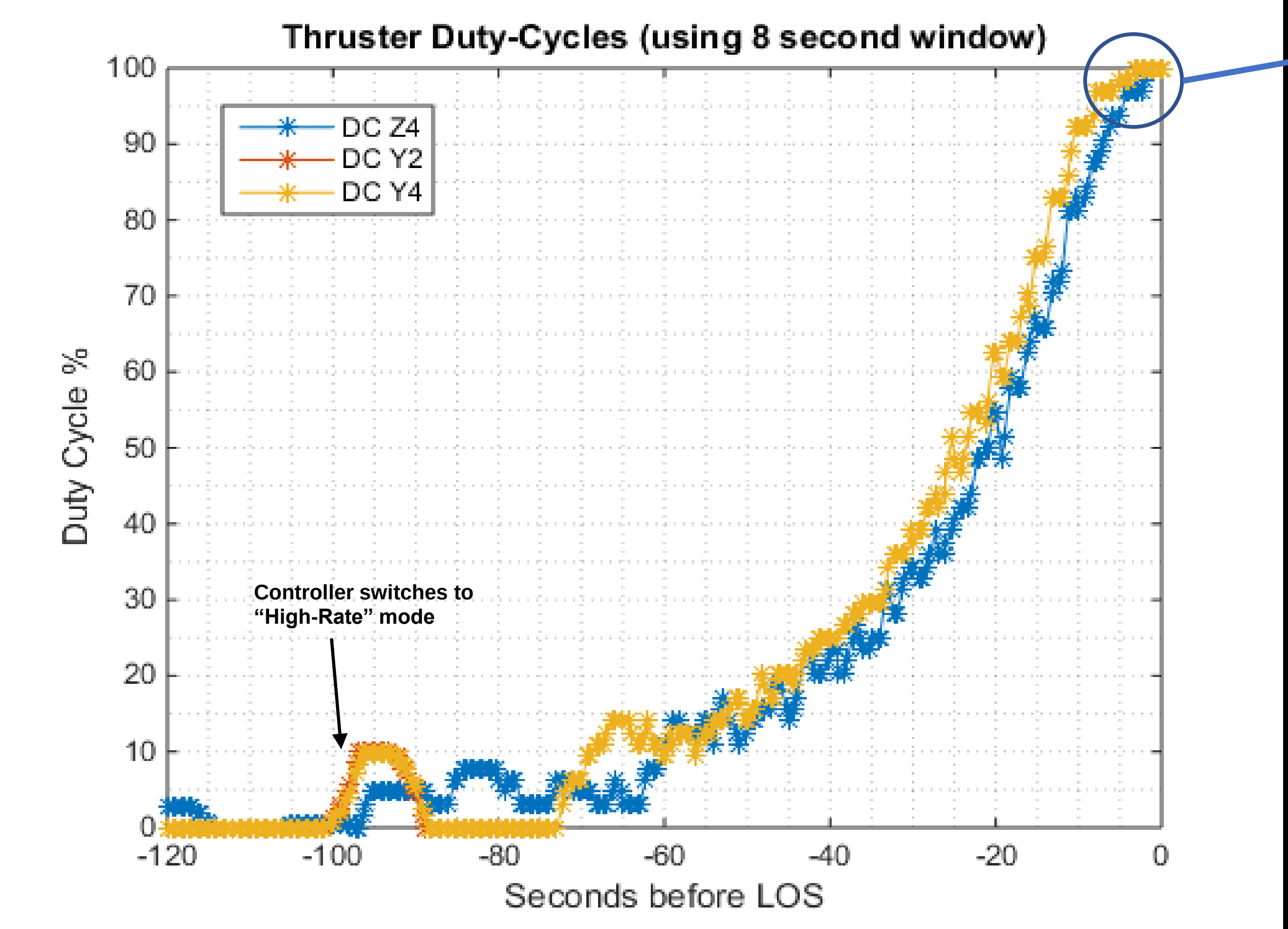

Figure: Thruster duty cycles for the last 2 minutes of flight.

Table: Thruster duty cycle for the last 20 seconds of flight

Time to LOS (sec)	Predicted Altitude (km)	Y2B/Y4B Pair Duty Cycle (%)	Z4B Duty Cycle (%)
-20	1540	62.5	25
-19	1533	50	87.5
-18	1526	100	75
-17	1520	87.5	62.5
-16	1513	75	87.5
-15	1506	100	75
-14	1500	87.5	87.5
-13	1493	100	75
-12	1486	87.5	100
-11	1480	100	100
-10	1473	100	75
-9	1467	100	100
-8	1460	100	100
-7	1453	100	100
-6	1447	100	100
-5	1440	100	100
-4	1434	100	100
-3	1427	100	100
-2	1421	100	100
-1	1414	100	100
0	1408	100	100

A Successful Grand Finale

- Benign dust environment.
- Stable spacecraft for imaging and rapid tracking.
- No changes needed for ground or flight software.
- No contingency plans deployed.
- No fault protection responses.
- Cassini was healthy until the end!

For more information

- More from the paper:
  - Additional risk assessments: radiation effects, bright body interference, trajectory deviations, and fault protection response
  - More AACS results
  - Contingency planning
- Come back tomorrow for more talks!
- Visit the Cassini website: https://saturn.jpl.nasa.gov

Questions?

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Backup Slides

Gravity Gradient Torque

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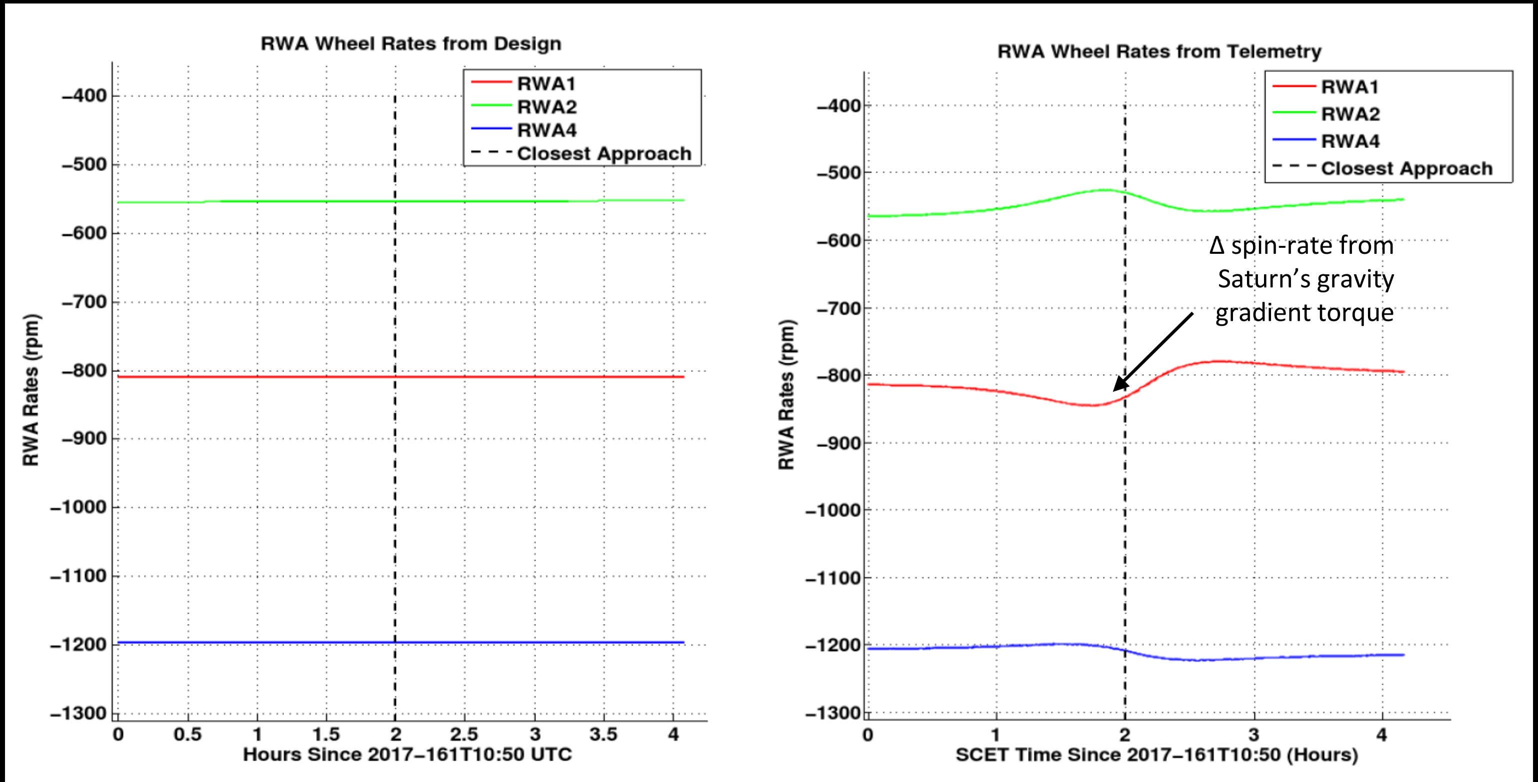
- Gravity gradient torque caused by variation of the planet's gravitational force applied over the spacecraft.
- The torque caused a change in angular momentum that could be seen in the reaction wheel speeds, even though the spacecraft remained at a fixed attitude.
- Gravity gradient torque previously seen in close flybys of Enceladus, Dione, and Rhea.



Figures: RWA wheel speeds as designed versus observed from telemetry.
Gravity gradient torque effects of Saturn (right plot) were evident in RWA wheel speeds.

Radiation Induced Hits on the Solid State Recorders

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